

Top Quark Production at the LHC

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Top quark production in proton proton collisions at the Large Hadron Collider (LHC) is reviewed using data collected by the ATLAS and CMS detectors. Most recent results on searches for new physics related to top quark production mechanism are included.

1. Introduction

The top quark is the most massive known fundamental constituent of nature, the only one with a mass of the same order magnitude of the electroweak symmetry scale. This property hints at an important connection with the still mysterious mechanism of spontaneous symmetry breaking. While the study of its production and decay allow for a precision test of the standard model (SM) predictions, the top quark is a ubiquitous ingredient for scenarios featuring physics beyond our present understanding [1]. In models where spontaneous symmetry breaking results from the presence of the Higgs boson or its supersymmetric extensions, the top quark is a crucial ingredient to constrain the Higgs mass range [2] and it is an important background to the corresponding searches. In alternative scenarios featuring extra dimensions or new strong forces, the top quark is often the preferred object new physics couples to so as to modify its production and/or its decay mechanism with respect to the SM predictions.

2. The Large Hadron Collider: producer of top quarks

Copious top quarks production is desirable to perform a detailed study of their properties. The proton-proton (pp) collisions with a center of mass (\sqrt{s}) of 7 TeV realized at the Large Hadron Collider (LHC) [3] allow to explore top quark production at unprecedented energy densities and abundance.

In summer 2011 the LHC has already achieved its performance goals for the year by reaching a peak luminosity $L = 2 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$, about ten times the one attained in 2010 ($2.1 \cdot 10^{32} \text{cm}^{-2} \text{s}^{-1}$) and by delivering an integrated luminosity per experiment $\int L dt = 2.5 \text{fb}^{-1}$, fifty times larger than the one delivered in 2010 (50pb^{-1}).

While the available luminosity encapsulates the space-time density of the LHC collisions, the other factor determining the number of events with top quarks produced at LHC is the cross section for producing top quarks in pp collisions and its dependence on \sqrt{s} . At the LHC top quarks are predominantly produced in top/anti-top quark pairs ($t\bar{t}$). The $t\bar{t}$ production

cross section, $\sigma_{t\bar{t}}$, is dominated by the gluon fusion process over quark annihilation due to the relative size of the gluon and quark parton distribution functions in the low proton momentum fraction region ($x \approx 0.025$) probed by $t\bar{t}$ events at the LHC [4]. The gluon fusion process accounts for about 85% of $\sigma_{t\bar{t}}$ in pp collisions at $\sqrt{s} = 7$ TeV (and 90% at $\sqrt{s} = 10$ TeV), thus inverting the hierarchy observed in $p\bar{p}$ collisions at Tevatron [5] ($x \approx 0.2$ for $t\bar{t}$ events). The value of $\sigma_{t\bar{t}}$ at LHC with $\sqrt{s} = 7$ TeV is estimated to be $165_{-16}^{+11} \text{pb}$ at approximate next-to-next-to-leading order (NNLO) [6]. The electroweak single top (or anti-top) production cross section is about one third of $\sigma_{t\bar{t}}$. It is characterized by the W boson mediated t -($\sigma_t = 64 \pm 3 \text{pb}$ [7]) and s -($\sigma_s = 4.6 \pm 0.3$ [8]) channel production accompanied by the Wt -channel where a virtual b -quark mediates the associated production of a W boson and a top quark in the final state ($\sigma_{Wt} = 15.7_{-1.4}^{+1.3} \text{pb}$ [9]).

The cross section for massive particles' production increases with a power law as a function of \sqrt{s} in $p\bar{p}/pp$ collisions [10]. At LHC with $\sqrt{s} = 7$ TeV $\sigma_{t\bar{t}}$ increases by about a factor twenty-three with respect to Tevatron. At the summer 2011 LHC luminosity, this results in the production of about one $t\bar{t}$ event every two seconds. With $\int L dt = 1 \text{fb}^{-1}$ the LHC expects about 2.4 times as many $t\bar{t}$ events as those available in Tevatron data with ninefold larger integrated luminosity.

3. ATLAS and CMS: observers of top quarks

As the top quark decays to a W boson and a b -quark about 100% of the times, the final state of a $t\bar{t}$ event is characterized by the number of W bosons decaying to a lepton-neutrino pair ¹. The case when both W bosons decay hadronically represents 45.7% of the events (fully hadronic channel), while 34.3% of the events feature only one W boson decaying to a lepton

¹The $W \rightarrow \ell \nu_\ell$ ($q\bar{q}'$) decay occurs 32.4% (67.6%) of the times where q is a light quark, ℓ is a lepton, ν_ℓ is the corresponding lepton neutrino.

(electron (e), muon (μ) or tau (τ) decaying to leptons) and a neutrino (ν_ℓ) (single lepton channel). The leptonic decay of both W bosons to e , μ or $\tau \rightarrow$ leptons occurs 6.5% of the time with the remaining 13.5% corresponding to double hadronic τ decays. The $t\bar{t}$ final state features b -jets from b -quark production, high p_T jets from hadronic W boson decays, at least one or two high p_T leptons and large missing transverse energy (E_T^{miss}) due to the neutrino in the W boson leptonic decays. The final states of single top quark and $t\bar{t}$ can be obtained from one another by swapping one $t \rightarrow Wb$ leg of the $t\bar{t}$ decay with a W boson (Wt channel) or one/two quarks (s and t -channels), one of which is a b -quark. The two final states then have similar backgrounds (single bosons (W , Z) plus jets, dibosons and Quantum Chromodynamics (QCD) multi-jet events) and they are background to each other.

Such complex final states require the full involvement of the two complementary, multi purpose detectors aimed at measuring the properties of leptons, hadrons and photons in the LHC pp collisions: ATLAS [11] and CMS [12]. They feature layers of sub-detectors radially expanding outwards with cylindrical symmetry around the line of the colliding proton beams. From the tracking devices to the electromagnetic and hadronic calorimeters to the muon stations, featuring different bending magnetic field (solenoidal in CMS, solenoidal and toroidal in ATLAS) each entire detector is at play in reconstructing events with top quarks efficiently selected by its three-(ATLAS) or two-(CMS) tier trigger system. The excellent data-taking performance of the two detectors allows each collaboration to analyze $\int L dt = 36 \text{ pb}^{-1}$ of data collected in 2010 and already $\int L dt = 0.2$ to 1.4 fb^{-1} of the $\int L dt = 2.5 \text{ fb}^{-1}$ of data recorded per experiment up to summer 2011². The values of $\int L dt$ are known at the level of 3.4% to 4.5%.

4. Ingredients for top quark detection with ATLAS and CMS

The multiple ingredients to reconstruct the final state of events with top quarks are the starting points of any top analysis.

Electrons [13, 14] are defined as isolated central objects ($|\eta_e| < 2.4(2.5)$ for ATLAS (CMS)) with large transverse momentum (p_T) ($p_T^e > 25$ (30) GeV for ATLAS (CMS)) combining the electromagnetic shower shape information of clusters in the calorimetry with the space-matched tracks reconstructed by the tracking system. ATLAS features an electron energy scale known within 0.3% to 1.6% (up to 1 TeV)

²As these proceedings are being written ATLAS and CMS have completed their 2011 data collection for pp collisions with $\int L dt \approx 5.2 \text{ fb}^{-1}$ recorded per experiment.

[13] while CMS ECAL scale is known within 0.6% to 1.5% [14]. Duplicate electrons are removed either as reconstructed objects recognized by the particle flow scheme used by CMS [16] or (similarly) as close-by jets with $\Delta R(e, \text{jet}) < 0.2$ ³ rejected by ATLAS.

Muons [17, 18] are isolated central ($|\eta_\mu| < 2.5$ (2.1) in ATLAS (CMS)), high p_T ($p_T^\mu > 20$ GeV) tracks obtained from a combined fit of information from the tracker and the external muon system. The p_T scale is known at about 1% level. An event is rejected when $\Delta R(\mu, \text{jet}) < 0.4$ (for ATLAS) or 0.3 (for CMS) for at least one jet, to help suppress contributions from non- W -boson derived muons (from flavour decays).

Jets [19, 20] are reconstructed by feeding particle flow objects (CMS) or calorimetric, three-dimensional, noise-suppressed clusters (ATLAS) to the anti- k_T algorithm. Calibrated jets are obtained with an (η , p_T) dependent weight from simulated “true” kinematic information. The resulting jets need to be central ($|\eta_{jet}| < 2.5(2.4)$ for ATLAS (CMS)) with high p_T ($p_{T, \text{jet}} > 25$ (30) GeV for ATLAS (CMS)). The energy scale uncertainty for jets ranges between $\approx 2\%$ and 8% as a function of η and p_T ⁴. The contributions to the uncertainty include physics modelling, calorimeter response and detector simulation.

Missing transverse energy is derived from the negative vector sum of four momenta of the objects in the event. In ATLAS [21] energy in calorimeter cells associated with high p_T objects is summed with the muon momentum and an estimate of the dead material loss. In CMS [22] more than one technique is used starting from calorimetric energy /momentum information, then adding track information to it and/or finally considering the full set of objects reconstructed with a particle flow technique. All the elements are calibrated according to the high p_T object they are associated with.

5. $t\bar{t}$ production: single lepton channel

Both ATLAS [23] and CMS [24] measured $\sigma_{t\bar{t}}$ using single lepton events. The final state is characterized by one high p_T , central lepton (e or μ) with at least three jets resulting from the hadronic decay of the top quark. While in ATLAS large E_T^{miss} and transverse mass of the leptonic W boson ($m_T(W)$) are required

³The ΔR distance between two particles with four-momenta i and j is defined as $\sqrt{(\phi_i - \phi_j)^2 + (\eta_i - \eta_j)^2}$ where ϕ_i , η_i (ϕ_j , η_j) are respectively the azimuthal angle and the pseudorapidity of particle i (j).

⁴The typical expected inclusive central jet p_T range for selected $t\bar{t}$ single lepton events at LHC with $\sqrt{s} = 7$ TeV is between 25 or 30 GeV (uncertainty ≈ 4 to 8%) and $O(250)$ GeV with a mean p_T of ≈ 70 GeV (uncertainty $\approx 2\%$).

to reduce the impact of QCD, in CMS these cuts are not applied as E_T^{miss} is used as a variable in a likelihood fit. The basic cuts select \approx ten to twenty (one) thousand events for $\int Ldt = 0.7\text{fb}^{-1}(36\text{ pb}^{-1})$.

The dominant backgrounds are $W + \text{jets}$ events and multi-jet events from QCD. Both these backgrounds are constrained from data. The $W + \text{jets}$ shape is derived from simulation; its normalization is left as a parameter for a likelihood fit to determine. (ATLAS sets its initial value and Gaussian constraints for the fit from the asymmetry in W boson production in pp collisions.) ATLAS derives the shape, the initial value for the QCD background normalization by combining the content of QCD-enriched control samples derived from non-isolated leptons with the probabilities that real lepton and fake leptons meet isolation requirements. CMS considers control samples based on events failing only the electron identification requirements. The final QCD normalization is a floating parameter in the likelihood fit (with data-driven constraint for ATLAS). The shape of smaller electroweak backgrounds from single top events, di-boson production and $Z/\gamma + \text{jets}$ is derived from simulation and the normalization is a fit-determined parameter.

In both analyses a discriminant is built from signal and background templates of kinematic quantities. ATLAS uses lepton η , the p_T of the leading jet and variable related to how spherical and how transverse the event is (aplanarity). CMS uses E_T^{miss} for events with three jets and the mass of the three-jet system with the highest vectorially combined p_T for the events with four or more jets. A binned maximum likelihood fit of the discriminant templates to the data is performed to extract the cross section for the signal and the backgrounds in either three-, four- and more than four-jet samples (ATLAS) or only in the three- and four-or-more-jet samples (CMS).

For ATLAS the likelihood fit includes systematic uncertainties as nuisance parameters to be constrained from data, thus resulting into a reduction from 20% to 70 % of their contribution. The ATLAS result using $\int Ldt \approx 0.7\text{ fb}^{-1}$ is $\sigma_{t\bar{t}} = 179.0 \pm 3.9$ (stat.) ± 9.0 (syst.) ± 6.6 (lumi.) pb with a total relative uncertainty of 6.6% where about 5% (in quadrature) is of systematic origin. CMS includes systematic uncertainties in the pseudo-experiment used to derive the Neyman confidence level (CL) belt. The CMS result for $\int Ldt = 36\text{ pb}^{-1}$ is $\sigma_{t\bar{t}} = 173 \pm 14$ (stat.) $^{+36}_{-29} \pm 7$ (lumi.) pb and it is dominated by systematic uncertainties (mostly jet energy scale) accounting for with 21% of the total 23% uncertainty.

6. Ingredients for top quark detection: enter b -jets

The remaining ingredient used in characterizing the top quark final state, b -jets, uses the fact that b -

hadrons are characterized by a non-zero observable flight distance from the primary vertex and the presence of tracks with non-zero distance of closest approach with respect to the primary vertex. These properties together with the number of tracks related to the secondary vertex and their energies are the basis for a series of discriminants that both ATLAS [26] and CMS [27] use to separate b -jets from other types of jets. In both cases the performance of the b -jet identification (b -tagging) is assessed by using b -jet enriched control samples while the rate of mis-tagging is obtained by events characterized by the negative values of secondary vertex properties. Large efficiencies at the level of 80% are coupled to mis-tagging probabilities around 10%, while lower efficiencies around 40% allow purer samples with only a 0.1% mis-tagging rate.

7. $t\bar{t}$ production: single lepton channel with b -tagging

The standard single lepton selection and background assessment outlined in section 5 are complemented by requiring at least one b -tagged central, high p_T jet. CMS [28] performs a maximum likelihood fit to the secondary vertex mass in the two dimensional plane of standard and b -tagged jet multiplicity. ATLAS [29] uses the same maximum likelihood fit to a four-variable discriminant used in [23], but it replaces the leading jet p_T with the average of the two largest jet b -tagging probabilities. In both cases systematic uncertainties are extracted from the fit as nuisance parameters. Both analyses use $\int Ldt = 36\text{ pb}^{-1}$. The results are $\sigma_{t\bar{t}} = 150 \pm 9$ (stat.) ± 17 (syst.) ± 6 (lumi.) pb for CMS and $\sigma_{t\bar{t}} = 186 \pm 10$ (stat.) $^{+21}_{-20} \pm 6$ (syst.) ± 6 (lumi.) pb for ATLAS. Both results have the same relative uncertainty of about 13%.

8. $t\bar{t}$ production: di-lepton channel

The di-lepton final state is analyzed by both ATLAS [30] and CMS [31]. After requiring a single lepton (ATLAS) or even a di-electron (CMS) trigger, the di-lepton final state is characterized by exactly (ATLAS) or at least (CMS) two opposite-sign high p_T central leptons (e or μ), at least two central, high p_T jets (from b -quarks) and large E_T^{miss} (in the di-electron or di-muon case) or large transverse activity ($H_T = \text{sum of } |p_T| \text{ of jets and leptons (ATLAS) or sum of leptons' transverse masses (CMS)}$). In addition events with di-lepton masses that are either Z boson-like or below 15 GeV are vetoed as the backgrounds are the same as the single lepton channel with the replacement of $W + \text{jets}$ with $Z/\gamma + \text{jets}$. In case at least one b -tagged jet is required the E_T^{miss} requirement is relaxed.

The fake lepton background deriving from QCD is

estimated from data. In a generalization of the technique used for single-lepton analyses (see section 5), the probability that either a loosely selected fake or a real lepton is selected in the signal region is derived in control samples enriched with real or fake leptons (ATLAS) (Z -like and low E_T^{miss} events respectively) or in a multi-jet enriched single loose-lepton sample (CMS). These probabilities are then combined with the number of di-lepton events featuring either one of the three combination of (tightly, loosely) selected lepton pairs (ATLAS) or only a pair of loosely selected leptons (CMS): the number of fake leptons in the signal region (i.e. tight leptons) is the result.

In parallel the Z/γ + jets background is obtained by subtracting the expected non- Z/γ + jets simulated-background from the observed number of events in the Z -mass window control region and scaling the resulting value with the simulated ratio of the expected number of Z/γ + jets events in the control region to the the number of the same events expected in the signal region. The remaining electroweak backgrounds are estimated from simulation. The expected signal to background ratio ranges from 8 to 10 with a good agreement between data and simulation for about 2500 (1100) events in $\int Ldt = 1.1 \text{ fb}^{-1}$ for CMS (0.7 fb^{-1} for ATLAS).

The value of $\sigma_{t\bar{t}}$ is extracted by a maximum likelihood fit to a counting experiment hypothesis only incorporating the number of signal events expected in the three channels, including the estimates of the backgrounds and adding systematic uncertainties as nuisance parameters in the fit. The results obtained by ATLAS using $\int Ldt \approx 0.7 \text{ fb}^{-1}$ with and without the requirement of at least one b -tagged jet are: $\sigma_{t\bar{t}} = 171 \pm 6 \text{ (stat.) } {}^{+16}_{-14} \text{ (syst.) } \pm 8 \text{ (lumi.) pb}$ (untagged) and $\sigma_{t\bar{t}} = 177 \pm 6 \text{ }^{+17}_{-14} \text{ (syst.) } {}^{+8}_{-7} \text{ (lumi.) pb}$ (≥ 1 b -tag). CMS untagged result with $\int Ldt = 1.14 \text{ fb}^{-1}$ is $\sigma_{t\bar{t}} = 169.9 \pm 3.9 \text{ (stat.) } \pm 16.3 \text{ (syst.) } \pm 7.6 \text{ (lumi.)}$. All results have a relative uncertainty around 11% that is already systematics-dominated. For ATLAS jet energy scale (5%) or b -tagging (5%) are dominant, while for CMS pile-up and lepton selection account for about 5% of the total uncertainty.

8.1. Using taus: the $\tau\mu$ channel

Both ATLAS [32] and CMS [33] have started using hadronic tau (τ) decays in the di-lepton final states. A high p_T muon is requested to be accompanied by at least one jet-seeded τ candidate with opposite sign to the muon, either resulting from a cut-flow-based algorithm run on particle flow objects (CMS) or detected by a boosted decision tree scheme (ATLAS). Then (at least) two jets and at least one b -tagged jet are required together with large E_T^{miss} and large H_T . The dominant backgrounds ($t\bar{t}$ and W + jets) are de-

rived from data either in the low jet multiplicity region (ATLAS) or by weighting a W + ≥ 3 jets enriched sample with the τ -faking probability derived from averaging two data-driven estimates in W + 1 jet sample and QCD enriched regions (CMS). The QCD shape is derived from a control region with non isolated muons and normalized to the low E_T^{miss} region.

The value of $\sigma_{t\bar{t}}$ is then obtained by scaling the number of signal events with the acceptance and luminosity. The number of signal events are obtained by either subtracting the estimated background (CMS) or by a likelihood fit to the distribution of the boosted decision tree variable used for τ -tagging (ATLAS). Such distribution is derived by taking the difference between samples with opposite sign and same sign $\tau\mu$ pairs (so as to cancel out the presence of most events where a gluon- or b -jet fakes a τ candidate).

The resulting cross sections using $\int Ldt = 1.08 \text{ fb}^{-1}$ are $\sigma_{t\bar{t}} = 142 \pm 21 \text{ (stat.) } {}^{+20}_{-16} \text{ (syst.) } \pm 5 \text{ (lumi.) pb}$ (ATLAS) and $\sigma_{t\bar{t}} = 148.7 \pm 23.6 \text{ (stat.) } \pm 26.0 \text{ (syst.) } \pm 8.9 \text{ (lumi.) pb}$. The results have comparable relative uncertainties of 24% (CMS) and 21% (ATLAS) with similar sizes for statistical and systematic uncertainties.

9. $t\bar{t}$ production: fully hadronic channel

The $t\bar{t}$ fully hadronic final state is analyzed by both ATLAS [34] and CMS [35]. Events are selected by requiring a multi-jet (at least 4 jets) trigger and at least six high p_T central jets with at least two b -tagged jets. In ATLAS no electrons or muons are allowed in the final state and small E_T^{miss} significance ($E_T^{miss}/\sqrt{s}(E_{T,calo})$) and large H_T are required. Both analyses reconstruct the events with a least-squares (χ^2) kinematic fit to the $t\bar{t}$ hypothesis. The dominant QCD background is derived from data by weighting events from an untagged multi-jet control sample with five or six jets with a data-driven b -tagging probability. The number of signal events is extracted from a likelihood fit to either the top quark mass distribution (also checked by a neural network discriminant) (CMS) or to the χ^2 distribution from the fit (ATLAS). The value of $\sigma_{t\bar{t}}$ is obtained by scaling the number of signal events with acceptance and luminosity. Systematic uncertainties are dominated by contributions from b -tagging, jet energy scale and background normalization. With $\int Ldt = 36 \text{ pb}^{-1}$ ATLAS sets a 95% confidence level upper limit of $\sigma_{t\bar{t}} < 261 \text{ pb}$. Using $\int Ldt = 1 \text{ fb}^{-1}$ CMS obtains $\sigma_{t\bar{t}} = 136 \pm 20 \text{ (stat.) } \pm 40 \text{ (syst.) } \pm 8 \text{ (lumi.)}$: this is already systematics-dominated with a relative uncertainty of 33%.

10. Combined results for $t\bar{t}$ production

Both ATLAS [36] and CMS [28] combine their measurements of $\sigma_{t\bar{t}}$ from the single lepton and di-lepton

channels as shown in figure 1. The combined results for $\sigma_{t\bar{t}}$ are:

ATLAS : $176 \pm 5(\text{stat.})_{-10}^{+13}(\text{syst.}) \pm 7(\text{lumi.})\text{pb}$,

CMS: $154 \pm 17(\text{stat.} + \text{syst.}) \pm 6(\text{lumi.})\text{pb}$.

These results do not include the latest untagged single-lepton measurement by ATLAS using $\int Ldt = 0.7 \text{ fb}^{-1}$ (see section 5) and the latest di-lepton measurement by CMS using $\int Ldt = 1.14 \text{ fb}^{-1}$ (see section 8). The relative uncertainty is in both cases at the level of 10%: it is comparable with the theoretical uncertainty and already systematics-dominated.

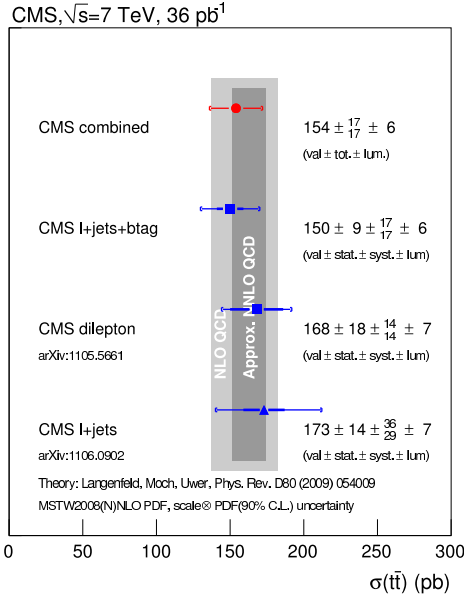
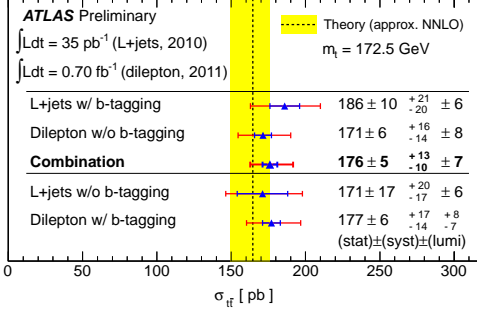


Figure 1: Available summaries and combinations of $\sigma_{t\bar{t}}$ measurements from ATLAS [36] (upper figure) and CMS [28] (lower figure). See text for comments on required updates.

11. Single top quark production

11.1. The t -channel

The single top t -channel events are selected by requiring one central, high p_T lepton (e or μ), large E_T^{miss} and $m_T(W)$ and exactly two or three jets with $|\eta_{\text{jet}}| < 4.5$ (ATLAS) or 5 (CMS). Both ATLAS [37]

and CMS [38] consider samples with and without b -tagging requirements and derive QCD and $W + \text{jets}$ normalization from data. CMS combines two results: a two-dimensional maximum likelihood fit to the data in the space of the angle between the lepton and the untagged jet in the top-quark rest frame and the η of the untagged jet; a Bayesian estimate of the cross section derived from a boosted decision tree discriminant. ATLAS uses a cut-based analysis involving jet angular variables, H_T and the leptonic top quark mass. The result is also confirmed by a maximum likelihood fit to a neural network output based on a set of thirteen discriminating variables. ATLAS uses $\int Ldt = 0.7 \text{ fb}^{-1}$ to obtain $\sigma_t = \sigma_{t\bar{t}} = 90 \pm 9 (\text{stat.})_{-20}^{+31} (\text{syst.})$ (with a significance of 7.6 standard deviations (s.d.)), while CMS result with $\int Ldt = 36 \text{ pb}^{-1}$ is $83.6 \pm 29.8 (\text{stat.} + \text{syst.}) \pm 3.3 (\text{lumi.}) \text{ pb}$ (with 3.5 s.d. significance).

Both results are systematics-dominated with the same relative uncertainty of 36%.

11.2. The Wt -channel

The Wt -channel single top events are searched for in the fully leptonic configuration by ATLAS [39] using the standard di-lepton selection and adding the requirement of exactly one central high p_T jet (from the b -quark of the top quark decay) and a cut on the azimuthal angle between the lepton and E_T^{miss} to reject $Z \rightarrow \tau\tau$ decays. The main backgrounds are derived from data control samples: QCD uses lepton isolation information as in section 5. The $Z/\gamma + \text{jets}$ background is extrapolated within the $(E_T^{\text{miss}}, \text{di-lepton mass})$ plane, the specific $Z \rightarrow \tau\tau$ decay is extrapolated from the region with low sum of the angles between the lepton and E_T^{miss} . Finally the dominant $t\bar{t}$ contribution is extrapolated from two-jet events. A cut-and-count analysis then uses a maximum likelihood fit to combine the channels by fitting systematic uncertainties as nuisance parameters. The good agreement between data and simulation induces ATLAS to set an observed (expected) 95% CL level upper limit on σ_{Wt} of 39 (41) pb using $\int Ldt = 0.7 \text{ fb}^{-1}$.

11.3. The s -channel

The s -channel single top production is searched for by ATLAS [40] by using the single lepton selection modified by the requirement of having exactly two high p_T central jets and using the same triangular cut on $m_T(W)$ for e and μ to reject QCD. Events with and without b -tagged jets are considered, while the analysis result requires two b -tagged jets. The estimate of QCD is derived from data by fitting the normalization of the E_T^{miss} shape derived in a sample enriched in electron-like jets. The $W + \text{jets}$ normalization is extrapolated from combining information from the un-

tagged sample and from the one and two-jet bins of the tagged samples. A cut and count analysis combines channels with a maximum likelihood where systematic uncertainties are constrained from data. The good data-to-simulation agreement supports setting an observed (expected) 95% CL limit on σ_s of 26.5 (20.5) pb with $\int Ldt = 0.7 \text{ fb}^{-1}$.

12. Top production as a window on new physics

A variety of alternative scenario can account for deviations from the SM in $t\bar{t}$ production. The presence of large mass resonances decaying preferentially to $t\bar{t}$ is a widely studied scenario [41]. At the highest $t\bar{t}$ masses ($M_{t\bar{t}}$) it produces a di-top-jet topology in which the final products of each top quark decay are closely merged into a single jet (boosted) [42]. The $t\bar{t}$ production can also result from the presence of a heavy partner of the top quark (T) which is pair-produced and decays to a top quark and a neutral stable particle (A_0) representing a good dark matter candidate. The resulting final state features a pair of top quarks with an increased amount of missing transverse energy from the dark matter candidates [43]. In addition the detection of same sign top quarks can signal flavour changing neutral currents (FCNC) proposed as a possible explanation for the recently observed discrepancy between data and SM predictions in the $t\bar{t}$ forward-backward asymmetry [44–46].

12.1. Search for FCNC-induced same-sign top pair production

CMS searched for same sign top quark pair production [47] by requesting two positive isolated leptons, at least two high p_T jets and large E_T^{miss} . The dominant background consists of single lepton $t\bar{t}$ events with one fake lepton and it is derived from a data control sample selected with loose electron isolation and identification requirements. The selected events show no excess over the background. A Bayesian technique is used to include systematic uncertainties and set a 95% credible interval in the production of same sign top pairs as a function of the mass of the mediating Z' and its right-handed chiral coupling. The preferred region for an FCNC-explanation of the $t\bar{t}$ forward-backward asymmetry is excluded. In particular for a Z' mass of 2 TeV a more stringent limit than the recent Tevatron one is set on the strength of effective four-fermion contact interactions ($\frac{C_{RR}}{\Lambda} < 2.7 \text{ TeV}^{-2}$).

12.2. Search for excess in $t\bar{t}$ production with large E_T^{miss}

ATLAS searched for an excess in $t\bar{t}$ events with large E_T^{miss} [48] with $\int Ldt = 1.08 \text{ fb}^{-1}$. The standard single lepton selection was enriched by requiring very large $E_T^{miss} (> 100 \text{ GeV})$, large $m_T(W)$ and vetoing events with b -tagged jets or an additional low p_T lepton. The dominant $W + \text{jets}$ and $t\bar{t}$ background is estimated from data: the shape is derived from low jet multiplicity events with b -tagging veto; the normalization results from the low $m_T(W)$ region. QCD background estimated from data (like in section 5) is found to be negligible. No excess is found in the selected data over the expected background. The event yields are used to build a frequentist statistic [49] to set a 95% CL limit for the cross section times branching for the $T\bar{T} \rightarrow t\bar{t} A_0 A_0$ reaction and as a function of A^0 mass (m_{A^0}) and T mass (m_T). For $m_{A^0} < 140 \text{ GeV}$, scenarios with $340 \text{ GeV} < m_T < 380 \text{ GeV}$ are excluded. In particular for m_{A^0} smaller than 30 GeV the $m_{A^0} = 410 \text{ GeV}$ scenario is excluded at 95% CL. Finally $(\sigma \times \text{BR}) = 1.1 \text{ pb}$ is excluded at 95%CL for $(m_{A^0}, m_{A^0}) = (420 \text{ GeV}, 10 \text{ GeV})$.

12.3. Search for excess in $t\bar{t}$ production versus $M_{t\bar{t}}$

Both ATLAS [50] and CMS [51] searched for excess resonant $t\bar{t}$ production in the single lepton channel. The standard single lepton selection is used in ATLAS with at least four jets and one b -tagged jet in the final state. CMS developed a boosted top quark selection in the single muon channel, requiring at least two jets with $p_T > 50 \text{ GeV}$ for which the leading jet p_T is larger than 250 GeV. One non-isolated muon is required with either a ΔR distance of 0.5 or a relative p_T of at least 15 GeV with respect to the spatially closest jet. Finally a large value for the sum the lepton p_T plus E_T^{miss} is required. The main backgrounds are estimated from data. For QCD ATLAS derives its shape from a jet-enriched sample normalized to the low E_T^{miss} region while CMS uses the events failing the two-dimensional muon selection cuts. The $W + \text{jets}$ normalization is extrapolated from small jet multiplicity events. After reconstructing the leptonic W boson using the W mass constraint with E_T^{miss} and the μ four momentum, the $t\bar{t}$ mass is calculated by either summing the leptonic W boson to the four leading p_T jets (ATLAS) or to the jets that are consistent with a back-to-back boosted di-jet topology (CMS).

No excess is observed and 95% Bayesian credible intervals are set for Z' and Randall-Sundrum (RS) KK-gluon production including systematic uncertainties by either integrated (CMS) or averaged (ATLAS) nuisance parameters. CMS uses $\int Ldt = 1.14 \text{ fb}^{-1}$ to set upper observed (expected) limits at 95% probability

on narrow Z' ($\Gamma_{Z'}/M_{Z'} = 1\%$) $\sigma \times BR$ at the sub-pb level for $M_{Z'} > 1.3$ TeV and at less than 0.2 pb for $M_{Z'} > 2.3$ TeV. No narrow resonance scenarios are excluded, however if a less-narrow Z' ($\Gamma_{Z'}/M_{Z'} = 3\%$) is considered, CMS excludes scenarios with $805 \text{ GeV} < M_{Z'} < 935 \text{ GeV}$ and $960 \text{ GeV} < M_{Z'} < 1060 \text{ GeV}$. ATLAS also excludes scenarios with KK-gluon masses below 650 GeV with 95% probability.

A search for resonant $t\bar{t}$ production is also carried out by ATLAS [52] in the di-lepton (e, μ) channel with $\int Ldt = 1.04 \text{ fb}^{-1}$. The standard di-lepton selection is applied and data driven estimates were derived for QCD and $Z/\gamma + \text{jets}$ backgrounds from a control sample selected with an E_T^{miss} -dependent Z -window for the di-lepton mass. No excess is found in the sum of H_T and E_T^{miss} . A 95% Bayesian credible interval is obtained for $\sigma \times BR$ for the production of RS KK-gluon including systematic uncertainties as integrated nuisance parameters. The standard scenario for RS KK-gluon production is excluded with 95% probability for KK Gluon masses below 0.84 TeV.

CMS also developed a search for boosted resonances in $t\bar{t}$ hadronic decays [53] triggered on events with at least one jet with very high p_T ($> 200 \text{ GeV}$). Two configurations are analyzed for $\int Ldt \approx 0.9 \text{ fb}^{-1}$. The “1+1” configuration requires at least two Cambridge-Aachen (CA) large cone ($\Delta R = 0.8$) jets with $p_T > 350 \text{ GeV}$ and large $\delta\phi$ separation and with both jets tagged as *top*-jets. Top-jet tagging is based on the consistency of the jet mass with the top quark mass, the presence of at least three sub-jets in the last two steps of the CA algorithm with a minimum mass of at least 50 GeV for at least one sub-jet pair. The “1+2” configuration requires at least three large cone CA jets featuring one leading top-tagged jet with $p_T > 350 \text{ GeV}$ and a second (third) “pruned” jet (i.e. with less soft, wide angle clusters) with $p_T > 200$ (30) GeV and large $\Delta\phi$ from the leading p_T jet. The second jet is requested to be recognized as a W -jet i.e. with a jet mass consistent with the W mass, two sub-jets and a maximum ratio of the sub-jet mass to the jet mass of 0.4. The second and third jet are required to form a jet with a mass consistent with the top mass. The dominant QCD background is obtained by weighting a di-jet control sample featuring one top-tagged jet with data-driven mis-tagging probability. The mis-tagging probability is obtained from the fraction of top/ W -tagged probe jets in QCD enriched high p_T di- and tri-jet events with one anti-top-tagged jet (failing a subset of top- or W -tagging cuts). The mass of the $t\bar{t}$ system is obtained by summing the top-jets in the “1+1” configuration or the top-jet, the W -jet and the closest jet to the W -jet in the “1+2” configuration. For the QCD background the untagged jet mass is flatly randomly chosen in the (140 GeV, 250 GeV) interval to provide similarity to the jets in the signal region. No excess is observed and a 95% Bayesian credible interval is derived for $\sigma \times BR$ for the pro-

duction of both Z' and RS-like KK-gluons, including systematic uncertainty as integrated nuisance parameters. Sub-pb limits are obtained on $Z' \sigma \times BR$ and scenarios with KK-gluon with a mass between 1 and 1.5 TeV are excluded with 95% probability.

13. Conclusions

Top quark production analysis at LHC is in full swing thanks to the combined performance of the collider and the associated detectors: a very rich program is already underway.

The value of $\sigma_{t\bar{t}}$ is measured in nearly all expected final states. It is consistent with the SM at $\sqrt{s} = 7 \text{ TeV}$ and most measurements are systematics-dominated, entering the realm of precision physics with $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \leq 10\%$. Single top production is clearly observed in the t -channel while more data is needed to observe it in the Wt and s -channel.

The rapidly increasing data-set and detector understanding is quickly opening unprecedented phase space for new physics searches linked to top quark production, ranging from resonances to dark matter candidates, whose mass sensitivity is by now breaking the 1 TeV barrier.

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